ON THE POSSIBILITY OF OBSERVING H_2 EMISSION FROM PRIMORDIAL MOLECULAR CLOUD KERNELS

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ABSTRACT

We study the prospects for observing H_2 emission during the assembly of primordial molecular cloud kernels. The primordial molecular cloud cores, which resemble those at the present epoch, can emerge around $1 + z = 20$ according to recent numerical simulations. The kernels form inside the cores, and the first stars will appear inside the kernels. A kernel typically contracts to form one of the first generation stars with an accretion rate that is as large as $\sim 0.01 M_\odot$ year^{-1}. This occurs due to the primordial abundances that result in a kernel temperature of order 1000K, and the collapsing kernel emits H_2 line radiation at a rate $\sim 10^{35}$ erg sec^{-1}. Principally $J = 5 - 3$ (v=0) rotational emission of H_2 is expected. At redshift $1 + z = 20$, the expected flux is ~ 0.01 μJy for a single kernel. While an individual object is not observable by any facilities available in the near future, the expected assembly of primordial star clusters on sub-galactic scales can result in fluxes at the sub-mJy level. This is marginally observable with ASTRO-F. We also examine the rotational $J = 2 - 0$ (v=0) and vibrational $\delta v = 1$ emission lines. The former may possibly be detectable with ALMA.

Key words: cosmology: observations — galaxies: formation — infrared: galaxies — ISM: molecules — submillimeter

1. INTRODUCTION

Observation of the first generation of stars presents one of the most exciting challenges in astrophysics and cosmology. Hydrogen molecules (H_2s) play an important role as a cooling agent of gravitationally contracting primordial gas (Saslaw & Ziploy 1967) in the process of primordial star formation. It has previously been argued that H_2 is an effective coolant for the formation of a globular cluster (Peebles & Dicke 1969), if such objects precede galaxy formation. The contraction of primordial gas was also studied in the pioneering work of Matsuda, Sato, & Takeda (1969). The observational feedback from such Population III objects was examined in Carr, Bond, & Arnett (1984). In the context of the CDM (Cold Dark Matter) scenario for cosmic structure formation, Couchman & Rees (1986) suggested that the feedback from the first structure is not negligible for e.g. the reionization of the Universe and the Jeans mass at this epoch (e.g. Haiman, Thoul, & Loeb 1996; Gnedin & Ostriker 1997; Ferrara 1998). Recent progress on the role of primordial stars formation in structure formation is reviewed in Nishi et al. (1998).

More recently, the first structures in the Universe have been studied by means of very high resolution numerical simulations (Abel, Bryan, & Norman 2000). The numerical resolution is sufficient to study the formation of the first generation of molecular clouds. According to their results, a molecular cloud emerges with a mass of $\sim 10^5$ solar masses as a result of the merging of small clumps which trace the initial perturbations for cosmic structure formation. Due to the cooling of H_2, a small and cold prestellar object appears inside the primordial molecular cloud. It resembles the core of molecular clouds at the present epoch. Their numerical results are consistent with other numerical simulations by Bromm, Coppi, & Larson (1999), whose results are consistent with those of Abel et al. (Bromm, Coppi, & Larson 2001). All the simulations predict that the primordial molecular clouds and their cores appear at the epoch of $1 + z \sim 20$ (z is redshift).

According to these results, the first generation of young stellar objects has a mass of $\sim$ 200 solar mass, density of $\sim 10^5$ cm^{-3}, and temperature of $\sim$ 200 K. We stress that these are cloud cores, and not stars. The resolution of the existing numerical simulations is inadequate to extend the dynamic range to actual star formation. Resort must be made to analytical arguments.

Inside the cores, a very dense structure appears. We shall call this a *kernel* for clarity of presentation. Its density increases to a value as high as $\sim 10^8$ cm^{-3} where the three-body reaction for H_2 formation occurs. Further evolution is by fragmentation (Palla, Salpeter, & Stahler 1983) and/or collapse (Omukai & Nishi 1998). In the current paper, we consider the case that the kernel collapses: the alternative case of fragmentation will be discussed in another paper. Recent theoretical work has suggested that fragmentation occurs if the

metallicity is above $10^{-3.5} \times Z_\odot$ where $Z_\odot$ is the solar metallicity (Bromm et al. 2001).

Omukai & Nishi (1998) show that the kernel collapses with a very large accretion rate. It is about 0.01 $M_\odot$ year^{-1}. This accretion rate is so high due to the cooling of H_2. The H_2 rotational and vibrational level transitions have wavelengths in the the rest frame infrared band. The recent numerical simulations suggest that these are emitted at $1 + z \sim 20$. The redshifted wavelength is detectable in the infrared – sub-mm bands. Of course, the predicted luminosity of individual kernels would not be expected to be extraordinary huge, although if the kernels are clustered, the assembly of kernels may be detected by future observational facilities. Hence, in this paper, we will consider observationally feasible conditions for the assembly of primordial kernels. Future telescope projects that are relevant are ALMA for the sub-mm range and ASTRO-F for the infrared range.

In §2, we estimate the expected luminosity from a single contracting kernel. In §3, we confirmed that the luminosity from the kernel is primarily due to the emission of H_2, and we examine which lines are dominant. In §4, the observational feasibility is discussed.

2. LUMINOSITY OF PRIMORDIAL MOLECULAR CLOUD KERNEL

According to the recent numerical simulations, molecular cloud cores appear prior to the formation of population III objects. Cores contain a dense and cool kernel, which has nearly the same physical properties as the initial conditions chosen by Omukai & Nishi (1998). Omukai & Nishi find that the kernel collapses in a freely falling manner and that the first prestellar object grows with a very high accretion rate. This is possible because of the cooling by line emission of H_2. As a result, they find that the accretion rate is $\sim 10^{-2}$ $M_\odot$ year^{-1}.

We are interested here in the possibility observing primordial prestellar objects. We express the accretion rate in terms of luminosity. It is convenient for us to estimate the rate of energy release owing to the high primordial accretion rate. To determine this, we must examine the gravitational energy where the accretion occurs. To examine the gravitational potential energy, we need to determine the mass distribution around the centre of the kernel, where the first star emerges. Also, we assume a spherical configuration for the mass distribution. According to Omukai & Nishi, a high accretion rate is realized if a similarity collapse occurs with the adiabatic heat ratio of 1.1 (e.g. Suto & Silk 1988). The density distribution is described as

$$\frac{\partial \ln \rho(r)}{\partial \ln r} = \frac{-2}{2-\gamma}. \tag{1}$$

Here, r is the radial distance from the centre, $\rho(r)$ is the mass density of atomic H, H_2 and

He, and γ is the specific heat ratio. We set the mass-density distribution of a protostellar-kernel with $\gamma = 1.1$ as $\rho_{\rm k}(r) = \rho_{\rm k0}(r/r_0)^{-2.2}$ where $\rho_{\rm k0}$ is 2.0×10^{-16} g cm^{-3} and r_0 is 0.01 pc. These values are appropriate for fitting the protostellar kernel of Omukai & Nishi.

Once the density distribution of the kernel is given, we can estimate the gravitational potential at a radius r: $\Phi(r) = GM(r)/r$ where G is the gravitational constant and $M(r)$ is the mass inside the radius r. Since the density is proportional to $r^{-2.2}$, we find $\Phi(r) = GM(r)/r = 4\pi G \rho_{\rm k0} r_0^{2.2}/0.8 r^{0.2}$. We are interested in the mass within r_0, then, $\Phi(r_0) = 2.0 \times 10^{11}$ erg mass^{-1} is obtained. Hence, as found from the dimension of "erg mass^{-1}" for the potential, we obtain the energy release rate corresponding to the accretion rate as being

$$L_{\rm acc} = \dot{M} \times \Phi(r_0) = 1.3 \times 10^{35} {\rm erg\ s^{-1}} \times \frac{\dot{M}}{0.01 M_{\odot} {\rm year}^{-1}} \tag{2}$$

As found in the next section, this release of energy is explained by the cooling of H_2 radiation.

3. H_2 EMISSION LINES

The large accretion rate of the first stellar object arises because of the cooling of H_2. Here, we also re-formulate the energy loss owing to line emission of H_2. To estimate the cooling by H_2, we should know the number fraction of H_2, $f_2(r)$, and the temperature of gas, $T(r)$, in the kernel. Both should have some spatial dependence. We use the fitting formula for Omukai (2000) which is adapted from Omukai & Nishi (1998). For $f_2(r)$ (solid line in Fig.1);

$$f_2(r) = 0.0001 + 0.495 \times \frac{\exp\left(\frac{n(r)}{10^{11.0}{\rm cm}^{-3}}\right) - \exp\left(\frac{n(r)}{10^{11.0}{\rm cm}^{-3}}\right)}{\exp\left(\frac{n(r)}{10^{11.0}{\rm cm}^{-3}}\right) + \exp\left(\frac{n(r)}{10^{11.0}{\rm cm}^{-3}}\right)} \tag{3}$$

where $n(r) = 10.0^8 {\rm cm}^{-3} (r/0.01\ {\rm pc})^{-2.2}$ (the maximum of $f_2(r)$ is set to be 0.5 by definition). For $T(r)$ (dashed line in Fig.1);

$$T(r) = 1000\ {\rm K} \left(\frac{n(r)}{10^{15.0}{\rm cm}^{-3}}\right)^{\frac{1}{15}}. \tag{4}$$

According to Omukai (2000), molecular cooling can be dominant below a number density of $\sim 10^{15.0}{\rm cm}^{-3}$. According to our estimates, the temperature is always smaller than 1000 K. We usually set $T_3 \equiv T/1000$ K. Line emission of H_2 occurs due to the changes among rotation and vibration states. As long as the large accretion occurs in the range 200 K – 1000 K (Omukai 2000), we can safely adopt the formulation of Hollenbach & McKee (1979)

for rotational and vibrational emission of H_2. Adopting their notation:

$$L_{\rm r} \equiv \left(\frac{9.5\times 10^{-22}T_3^{3.76}}{1+0.12T_3^{2.1}}\exp\left[-\left(\frac{0.13}{T_3}\right)^3\right]\right) + 3.0\times 10^{-24}\exp\left(-\frac{0.51}{T_3}\right) \quad {\rm erg\ s^{-1}}, \tag{5}$$

we estimate the cooling rate as

$$\Lambda({\rm rot}) = n_{\rm H_2}L_{\rm r}(1+\zeta_{\rm Hr})^{-1} + n_{\rm H_2}L_{\rm r}(1+\zeta_{\rm H_2r})^{-1} \quad {\rm erg\ cm^{-3}\ s^{-1}}, \tag{6}$$

where $\zeta_{\rm Hr} = n_{\rm Hcd}({\rm rot})/n_{\rm H}$, $\zeta_{\rm H_2r} = n_{\rm H_2cd}({\rm rot})/n_{\rm H_2}$, $n_{\rm Hcd}({\rm rot}) = A_J/\gamma_J^{\rm H}$, $n_{\rm H_2cd}({\rm rot}) = A_J/\gamma_J^{\rm H_2}$, and A_J is the Einstein A value for the J to $J-2$ transition; $\gamma_J^{\rm H}$ is the collisional de-excitation rate coefficient due to neutral hydrogen; and $\gamma_J^{\rm H_2}$ is that due to molecular hydrogen. The first term of $L_{\rm r}$ denotes the cooling coefficient due to the higher rotation level ($J > 2$) and the second one due to $J = 2 \to 0$ transition. The vibrational levels of both terms are set to be zero. For our parameters of interest ($250 < T < 1000$; and $n > 10^8$ cm^{-3}), both ζs are much smaller than unity for dominant levels of J because of the low temperature. This is because the maximum A_J values are at most 3.0×10^{-7} sec^{-1}. As a result, these correction factors are found to be $1+\zeta \sim 1.0$.

For the vibrational transitions;

$$L_{\rm v} = 6.7\times 10^{-19}\exp\left[-\left(\frac{5.86}{T_3}\right)^3\right] + 1.6\times 10^{-18}\exp\left(-\frac{11.7}{T_3}\right) \quad {\rm erg\ s^{-1}}, \tag{7}$$

then, we get cooling rate as being

$$\Lambda({\rm vib}) = n_{\rm H_2}L_{\rm v}(1+\zeta_{\rm Hv})^{-1} + n_{\rm H_2}L_{\rm v}(1+\zeta_{\rm H_2v})^{-1} \quad {\rm erg\ cm^{-3}\ s^{-1}}, \tag{8}$$

where $\zeta_{\rm Hv} = n_{\rm Hcd}({\rm vib})/n_{\rm H}$, and $\zeta_{\rm H_2v} = n_{\rm H_2cd}({\rm vib})/n_{\rm H_2}$. Here, $n_{\rm Hcd}({\rm vib}) = A_{ij}/\gamma_{ij}^{\rm H}$, and $n_{\rm H_2cd}({\rm vib}) = A_{ij}/\gamma_{ij}^{\rm H_2}$ where A_{ij} is the Einstein A value for the i to j transition; $\gamma_{ij}^{\rm H}$ is collisional de-excitation rate coefficient due to neutral hydrogen; and $\gamma_{ij}^{\rm H_2}$ is that due to molecular hydrogen. In our formula, only the levels of $v = 0, 1$ and 2 are considered. This is sufficient since the temperature is lower than 1000 K. The first term of $L_{\rm v}$ is a cooling coefficient of $\delta v = 1$ and the second term is that of $\delta v = 2$. The second term has no effect on our conclusion because of the low temperature. Combining Eq.(6) and Eq.(8), we obtain the total cooling rate as $\Lambda^{\rm thin} = \Lambda({\rm rot}) + \Lambda({\rm vib})$ erg cm^{-3} s^{-1} in the optically thin regime.

We need a cooling function which can be used in the optically thick regime. Then, adopting the following extension of $L^{\rm thin}$, we estimate the cooling rate as:

$$L^{\rm thick} = L^{\rm thin}\frac{1-\exp(-\tau)}{\tau}\exp(-\tau_{\rm cont}) \tag{9}$$

where $L^{\rm thin}$ is representative of each term of $L_{\rm r}$ and $L_{\rm v}$, and τ is determined for each $L^{\rm thin}$. The effect of the continuum absorption below 2000 K is denoted by $\exp(-\tau_{\rm cont})$, in which

$$\tau_{\rm cont} = \rho(r)\lambda_{\rm J}\left[4.1\left(\frac{1}{\rho(r)} - \frac{1}{\rho_0}\right)^{-0.9} T_3{}^{-4.5} + 0.012\rho^{0.51}(r)T_3^{2.5}\right] \tag{10}$$

according to the estimate of Lenzuni, Chernoff, & Salpeter (1991) who obtain a fitting formula for the Rossland mean opacity in a zero-metallicity gas. Here, $\lambda_{\rm J}$ is the Jeans length and ρ_0 is 0.8 g cm^{-3}. Their fitting formula is reasonable if we consider the temperature range $T > 1000$ K. Our lowest temperature of the collapsing kernel is about 300 K. Then, their formula may not be appropriate, while it gives an upper limit if we adopt $\tau_{\rm cont}$ of 1000 K instead of really having $\tau_{\rm cont}$ below 1000 K. For all of our estimates, $\tau_{\rm cont}$ is sufficiently smaller than unity. Then, we can neglect the effect of continuum absorption.

We shall estimate τ for each line. Defining the suffix of i as the upper energy level and j as the lower energy level, we define τ_{ij} as τ for each line emission.

$$\tau_{ij} = \frac{A_{ij}c^3}{8\pi\nu_{ij}^3}\frac{n(x,i)g_i}{g_j}\frac{\lambda_{\rm J}}{2\delta v_D}. \tag{11}$$

Here, A_{ij} is a transition rate from the i state to the j state; ν_{ij} is the central frequency of emission in the rest frame; c is the speed of light; g_i and g_j are statistical weights for i and j respectively; $\lambda_{\rm J}$ is the Jeans length ($[2k_{\rm b}T(r)/\mu(r)m_{\rm H}]^{0.5} \times [3\pi/32G\rho(r)]^{-0.5}$); $k_{\rm b}$ is the Boltzmann constant; $\mu(r)$ is mean molecular weight; and $\delta v_D = [2k_{\rm b}T(r)/\mu(r)m_{\rm H}]^{0.5}$ is the velocity dispersion. The procedure of Jeans length shielding is useful for a simple analytical analysis (Low & Lynden-Bell 1976; Silk 1977). The population density of $n(x,i)$ for rotational level is estimated with the statistical weight of $g_J = 2J+1$ ($i.e.i \rightarrow J$). The suffix of x denotes each species. We consider $n({\rm H_2}, J)$ up to the upper level of J=5, which is selected since $J = 5$ is a dominant rotational level for our fitting formulae of Eq.(1), Eq.(3) and Eq.(4) as checked below. Then, we assume $n({\rm H_2}, J>2)/n({\rm H_2}, J=2) = 27/5$

In our calculation to obtain Eq.(11), for a rotational transition with $v = 0$, $A_{2,0} = 2.94 \times 10^{-11}$ sec^{-1}; and $A_{J,J-2} = 5A_{2,0}/162 \times J(J-1)(2J-1)^4/(2j+1)$ sec^{-1} are considered. For a vibrational transition, $A_{10} = 8.3 \times 10^{-7}$ sec^{-1}; $A_{21} = 1.1 \times 10^{-6}$ sec^{-1}; and $A_{20} = 4.1 \times 10^{-7}$ sec^{-1} are considered.

To find the dominant rotational emission, we calculate

$$J_{\rm max} = \frac{\int_{\rm kernel} 4\pi r^2 n(r)J(T(r))f_2(r)dr}{\int_{\rm kernrl} 4\pi r^2 n(r)f_2(r)dr} \tag{12}$$

where

$$J(T(r)) = \left(\frac{7}{2} \times \frac{T(r)}{85.2\ {\rm K}}\right)^{0.5}. \tag{13}$$

Here, $J(T(r))$ means the dominantly contributing J-level to the statistical weight at temperature of $T(r)$ (Silk 1983). Using our fitting formula of $f_2(r)$ and $T(r)$, we find $J_{\rm max}$ is about 5. Then, we regard that the dominant rotational line cooling due to the first term of Eq.(5) is the $J = 5-3$ transition. To estimate the luminosity via $L^{\rm thick}$ of Eq.(9), hence, we use $A_{5,3}$ since the $J = 5$ ($v = 0$) level is dominant. For $J = 2-0$ ($v = 0$) transition (the second term of Eq.(5)), we use $A_{2,0}$ to find $L^{\rm thick}$. The second term of Eq.(7) is always much smaller than the other terms, and we ignore it here.

The estimated total luminosity ($\int_{\rm kernel} 4\pi r^2 \Lambda dr$) with modified $L^{\rm thick}$s is 6.7×10^{34} erg s^{-1}. This is comparable to the luminosity estimated in §2. Thus, we confirm that the large accretion rate is possible owing to H_2 cooling. The emission fraction is 0.82 for the rotational transitions with $J > 2$; 0.12 for rotational transitions of $J = 2-0$ ($v = 0$); and 0.06 for vibrational transition of $\delta v = 1$. Note that the fraction of $J > 2$ is not much larger than the fraction of $J = 2-0$ ($v = 0$) transition. This is caused by the optical depth effect. If we adopted unity for the escape probability (i.e. any τ much smaller than unity), we would find the result that there is dominance of $J > 2$ rotational cooling. For the same reason, the fraction of vibrational cooling can be smaller than that of $J = 2-0$ ($v = 0$).

The line broadening is estimated to be $\sim \delta v_{\rm D}$ in the dimension of velocity. Adopting this, the luminosity per Hz (T=1000 K is assumed) is the following; The rotation emission of $J = 5-3$ (3.1×10^{13} Hz; 9.7×10^{-3} mm) is 1.9 $\times10^{26}$ erg Hz^{-1}, the rotation emission of $J = 2-0$ (1.1×10^{13} Hz; 2.8×10^{-2} mm) is 7.9 $\times10^{25}$ erg Hz^{-1}, and the vibration emission of $v = 1-0$ (1.2×10^{14} Hz; 2.4×10^{-3} mm) is 3.4 $\times10^{24}$ erg Hz^{-1}.

4. OBSERVATIONAL FEASIBILITY

In the current paper, we need the observational frequency and wavelength which are redshifted. For the three lines; we get 1.6×10^{12} Hz; 1.9×10^{-1} mm for $J = 5-3$, 0.53×10^{12} Hz; 5.6×10^{-1} mm for $J = 2-0$, and 6.1×10^{12} Hz; 4.9×10^{-2} mm for $\delta v = 1$. The adopted $1+z$ is 20 according to the results of recent numerical simulations.

To find the observed flux, we determine the distance to the object. Then, we calculate it numerically from the following standard formula:

$$D_{19} = \frac{c}{H_0} \int_0^{19} \frac{dz}{(\Omega_\Lambda + \Omega_{\rm M}(1+z)^{3.0})^{0.5}} \tag{14}$$

where H_0 is the Hubble parameter and used 75 km sec^{-1} Mpc^{-1}, Ω_Λ is the cosmological constant parameter, and $\Omega_{\rm M}$ is the density parameter. We consider the case $\Omega_\Lambda + \Omega_{\rm M} = 1$. Adopting D_{19}, we obtain the observed fluxes of each of the lines. The results are summarized

in table 1. Although the line-broadening is estimated from $\nu_0 \delta v_{\rm D}/c$, we also correct it with redshift effect (ν_0 is the central frequency). For each of the parameter sets of $(\Omega_\Lambda, \Omega_{\rm M})$, we obtain $D_{19} = 0.62 \times 10^{10}$ pc $(\Omega_\Lambda = 0, \Omega_{\rm M} = 1)$, $D_{19} = 1.00 \times 10^{10}$ pc $(\Omega_\Lambda = 0.7, \Omega_{\rm M} = 0.3)$, and $D_{19} = 4.58 \times 10^{10}$ pc $(\Omega_\Lambda = 0.9, \Omega_{\rm M} = 0.1)$. According to Table 1, the rotational line of $J = 5 - 4$ (v=0) is 0.07 μJy; 0.05 μJy for $J = 2 - 0$ (v=0); and 0.001 μJy for $\delta v = 1$ if $\Omega_{\rm M} = 1$. Thus, we find that a single kernel is not observable by any available observational facilities in the near future. The expected flux is too small.

However we note that if the kernels are assembled on a galactic scale, the assembly can be detected by ongoing projects. We shall estimate the number of kernels in a primordial galaxy. Firstly, we must consider the lifetime of a H_2 emission kernel. It may be 10^4 years for a 100 $M_\odot$ star at the specified accretion rate of $0.01 M_\odot$ year^{-1}. A $10^6 M_\odot$ cloud is expected to form 1000 such stars at a plausible efficiency. Taking its lifetime to be 10^5 years as the free-fall time of a $10^6 M_\odot$ cloud, we find that its luminosity is 100 $L_{\rm acc}$ (see Eq.(2) for definition of $L_{\rm acc}$).

Next, we consider an entire primordial galaxy with $10^{11} M_\odot$. It may form 10^9 supernovae over its entire lifetime. We assume that it makes 10^7 primordial massive stars, since this number of massive stars gives enrichment to roughly 1 percent of solar metallicity. If the burst of formation of primordial molecular cloud kernels occurs in the central region of the primordial galaxy (we postulate 1 kpc as the size of the kernel-forming region), then there are 10^4 such giant molecular clouds with $10^6 M_\odot$ in the kernel-forming region. During this phase, the cumulative luminosity would be 10^6 $L_{\rm acc}$. It seems that the predicted line luminosity would be easy to observe. However, the dynamical time-scale in the kernel forming region may be 10^7 years (e.g. the duration of the starburst). Then, we obtain 10^4 $L_{\rm acc}$ for the luminosity of the primordial galaxy undergoing its first star formation burst, conservatively assuming 10^5 years as the life-time of giant molecular clouds. Finally, for H_2 emitting protogalaxies, we obtain 0.7 mJy for $J = 5 - 3$, 0.5 mJy for $J = 2 - 0$ and 0.01 mJy for $\delta v = 1$ $(\Omega_{\rm M} = 1.0)$.

Thus, the rotational emissions of $J = 5 - 3$ and $J = 2 - 0$ are at sub-mJy flux levels. Those frequencies enter into the sub-mm and far-infrared bands if the kernels form at $1 + z = 20$. These are observational ranges of ALMA and ASTRO-F. According to the current status of the instrumentation for ALMA, 80-890 GHz is the allowed detectable range. It is feasible for our prediction of the redshifted H_2 emission of the $J = 2 - 0$ line. Unfortunately, however, the transmission is bad for the predicted feature at 530 GHz because of the atmosphere of the Earth. Then, it may be necessary to detect H_2 emission from a protogalaxy forming later than $1 + z = 20$. We note that '$1 + z = 20$' is obtained by taking $\Omega_M = 1$. If $\Omega_M < 1$, which seems to be reasonable if $\Omega_\Lambda = 0.7$, the formation of kernels is delayed. Then, we

can expect to detect emission at a higher frequency than 530 GHz and detection should be feasible of the H_2 emmision from the assembly of the primordial molecular kernels.

For the case of the $J = 5 - 3$ line, this is observable at 194 μm wave-length. This is in the allowed range of ASTRO-F (2-200 μm). At the wavelength of 200 μm, unfortunately, it is difficult to detect sub mJy-level fluxes because of the properties of the detectors. If a higher rotational transition than $J = 5 - 3$ dominates, the observations are more suitable for the allowed range of ASTRO-F. The higher transitions emit more energetic photons, and enter into the possible range of ASTRO-F. This may be possible if the external radiation field (e.g. Susa & Umemura 2000) has positive feedback on the primordial kernels. Thus, although we need a very specific condition in order to detect H_2 emitting protogalaxies, it may be possible to achieve this goal with future observational facilities.

Here, we advocate a deep blank field survey. The unit area for the survey can be estimated by the number density of QSOs, since QSOs are believed to form at high density peaks during cosmic structure formation. The burst of primordial kernel formation may be expected in the environment where QSOs can form. The most recent and reliable number density of QSOs is determined by Miyaji, Hasinger & Schmidt (2000). According to their luminosity function of soft X-ray AGNs, a typical number density (e.g. their figure 11) is about 10^{-6} h_{50}^{3} Mpc^{-3} beyond $z \sim 3$. They have assumed that Hubble parameter is 50 km/s/Mpc. Then, a unit covering area for a single QSO at a fixed redshift (i.e. a fixed distance) is typically 10^4 h_{50}^{-2} Mpc^2. The proper transverse size of an area, $D_{\rm size}$, as seen by us, is its comoving size times the scale correction factor at the time of emission; $\delta\theta D_{19}/20$ at $1 + z = 20$, where $\delta\theta$ has the units of radians. Hence the unit area needed for our blank field survey is estimated to be 7.6×7.6 degree^2 if $D_{\rm size} = 66.6$ Mpc, $D_{19} = 10^{10}$ pc, and $H_0 = 75$. The field of view of ALMA is about 10×10 arcsec^2. Thus, we need a huge amount of observing time to survey the expected area. The field of ASTRO-F for the long wavelength detector is 12.5×2.5 arcmin^2. Although ASTRO-F plans to survey nearly all the sky, the detection limit for the survey mode is at 10 mJy level and we cannot expect to detect H_2 emission. We need good pointing and long exposure-time for the entire area of 7.6×7.6 degree^2. Then, the pointing mode of ASTRO-F may be suitable. It can detect line emission at the mJy level in a single pointing exposure. To detect the predicted sub-mJy level flux, we need to expose the same region several times. As a result, we can expect that an H_2 emitting protogalaxy could be found near the oldest QSO via deep and off-centred (i.e. avoiding saturation) spectroscopy using the pointing mode of ASTRO-F.

It might be difficult to justify the necessary observing time for a blank field survey. In such a situation, we need to specify the observational target. Which object is suitable for our first observations? One possibility would be unidentified SCUBA sources (e.g. Smail,

Ivison, & Blain 1997). These are believed to have been detected at high redshift owing to the so-called "negative k-correction". As long as they are primordial galaxies, the possible range of z for SCUBA objects is from 3 to 10. If $z = 10$-SCUBA objects are observed by near-future facilities, it may be possible to detect emission from H_2 at the sub-mJy level. But, in this case, the background radiation from dust prevents us from confirming H_2 line emission. To resolve this, a high dispersion spectrograph is needed. Furthermore, if the SCUBA objects are metal-rich primordial galaxies, the primordial molecular cloud evolution favours the fragmentation scenario (Bromm et al. 2001), and low mass star formation. The criterion of Bromm et al. for being at metallicity below $10^{-3.5} \times Z_{\odot}$ to allow massive primordial star formation is only marginally satisfied at this redshift, as would be required to allow dominant H_2 cooling as suggested by Omukai (2000).

5. SUMMARY

One of the main goals of cosmology is to find the first generation of stars. When they form, strong H_2 emission is expected. We have examined the observational feasibility of detection. According to our analysis, $J = 5 - 3$ and $J = 2 - 0$ rotational emission are expected (at $v = 0$). Protogalaxies can have sub-mJy fluxes when the first stars form at $1 + z = 20$ as an assembly. It seems that these systems are marginally detectable by ALMA and ASTRO-F. However, the transmissivity of air for the emission of $J = 2 - 0$ is low for the ALMA project, and the wavelength edge of the filter for the far-infrared band is not sufficiently sensitive for the $J = 5 - 3$ line. Thus if future telescopes can detect H_2 emission from primordial molecular cloud kernels, the kernels and first stars have formed after $1 + z = 20$ and/or the temperature of the kernel should be larger than predicted in the simplest models.

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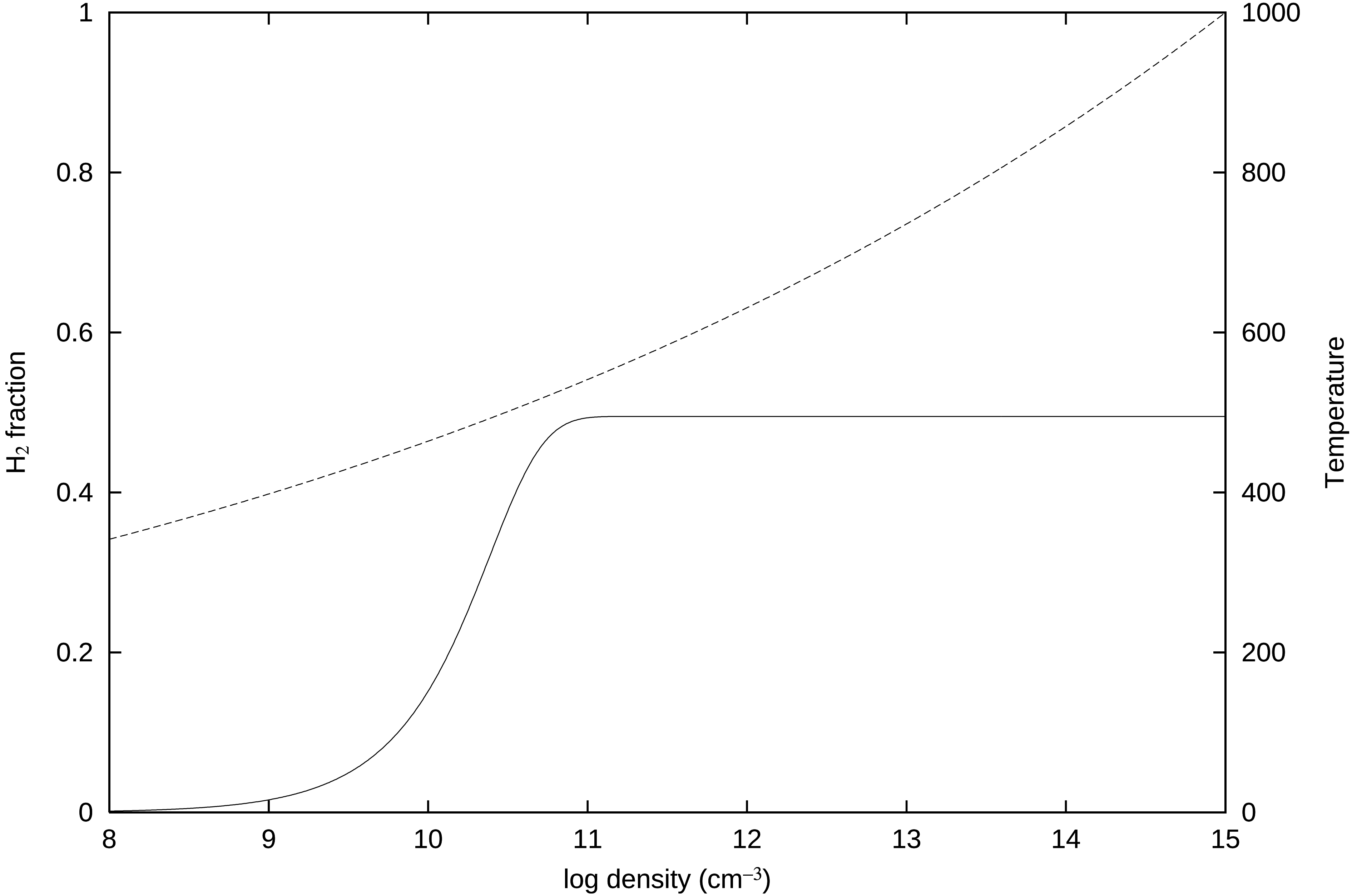
Table 1: Expected Emission Lines

—	$J = 5 - 3$	$J = 2 - 0$	$\delta v = 1$	Ω_m	Ω_Λ	D_{19} (10^{10} pc)
ν (10^{13} Hz; $z = 0$)	3.09	1.06	12.21	–	–	–
ν (10^{12} Hz; $z = 19$)	1.55	0.53	6.11	–	–	–
λ (10^{-3} mm; $z = 0$)	9.71	28.29	2.46	–	–	–
λ (10^{-3} mm; $z = 19$)	194.2	565.8	49.2	–	–	–
L_ν (10^{26} erg sec^{-1} Hz^{-1})	1.87	0.79	0.034	–	–	–
f_ν (10^{-8} Jy; $z = 19$)	7.34	5.32	0.148	1.0	0.0	0.62
f_ν (10^{-8} Jy; $z = 19$)	2.85	2.07	0.058	0.3	0.7	1.00
f_ν (10^{-8} Jy; $z = 19$)	1.29	0.94	0.026	0.1	0.9	1.48

FIGURE CAPTIONS

Fig.1 — Density–H_2 fraction relation (solid line) and Density–Temperature relation (dashed line) are depicted. Using Eq.(1), we translate them to Radius–Density and –Temperature relations, respectively.

FIGURE 1



1
0.8
0.6
0.4
0.2
0
H2 fraction
1000
800
600
400
200
0
Temperature
8
9
10
11
12
13
14
15
log density (cm−3)